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Design and Fabrication of End Parts for the First High Field Magnet Mechanical Model[*]

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1. Introduction

Fermilab, in collaboration with LBNL and KEK, is working on the design of a high field Nb_3Sn dipole magnet (of field strength 11 T) for use in future Very Large Hadron Collider (VLHC) machine. The conceptual design for the first magnet is provided in [1]. This design is based on a 2-layer $\cos\theta$ coil structure with a cold iron yoke. It was decided to build a mechanical model before building an actual magnet to verify our production technology. Since Nb_3Sn cable was not available initially, it was decided to build this first HFM mechanical model using NbTi cable from LHC project. This note provides a brief summary of the design and manufacturing aspects of the coil end parts for the first mechanical model magnet. The goals for this first mechanical model are as follows:

- to check ROXIE [2] code for design of cross section and magnet end parts,
- to select CAD-CAM software for end parts design and manufacturing,
- to find cheap technology to fabricate end parts,
- to set up the equipment and tooling necessary for coil fabrication,
- to get experience with handling insulation and to study insulation properties at different production steps,
- to verify the coil impregnation procedures and to check the quality of the impregnated coils,
- to verify the chosen assembly technique, and
- to measure mechanical properties of the wound and impregnated coils.

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2. End Parts Design

2.1 Cross-section optimization

Fig. 1 shows the cross section of the dipole model magnet, which is based on a 5-block design. The geometric position of coil block arrangements in the cross section was calculated from given input data such as the number of blocks, number of conductors per block, cable dimensions, radius of the winding mandrel, and positioning and inclination angle of the blocks. Table 1 provides the relevant input geometrical data for the model magnet cross-section, whereas cable dimensions and properties are provided in Table 2. The magnet cross-section and the coil ends could be optimized using program ROXIE, which utilizes both deterministic and stochastic (genetic algorithms) methods for solving the constraint vector-optimization problem associated with the design of superconducting magnets. ROXIE also allows optimization of the cross-section by an appropriate placement of the coil blocks to find a coil cross-section with a part compensation of the persistent current effects. However, since the goals for this first mechanical model were to verify our production technology and assembly techniques, it was decided not to spend further resources in optimizing the magnetic field within the bore of the mechanical model.

2.2 Coil end geometry and field optimization

The coil ends were designed with the objectives of maximizing the radius of curvature in the end and to apply as little '*hard-way*' strain as possible to the cable. ROXIE also allows shifting of the relative positions of the coil blocks to optimize the integrated multipole field. However, this feature was not used for the first mechanical model due to the reason already mentioned before. The input parameters which were used for the generation of the coil ends are the *z* position of the first conductor of each coil block and its inclination angle. The conductors were aligned on the winding mandrel and not to the outer radius of the end-spacers.

ROXIE uses a constant perimeter approach to define the coil ends. The upper edge of the conductor is assumed to be of elliptical or hyper-elliptical shape, in the developed plane defined by its radial position in the straight section. The position of the lower edge is then computed by assuming constant perimeter. Fig.2 shows a graphical representation of the inner and outer lead end coils for this model magnet obtained from ROXIE.

As part of the coil end design process, it was made sure that the parameter *bulge* (maximum/middle width) does not get larger than 1.1. Since the cable does not deform a lot, a *bulge* of more than 1.1 gives rulings which make sense mathematically but not physically. A large value of the parameter *bulge* can be corrected by inclining the blocks more or by adding additional spacers or inter-turn fillings. Also a *bulge* of more than 1.1 can cause lifting off the cable from the mandrel, after winding. ROXIE also outputs the values of '*hard-way*' strain and '*easy-way*' strain for all the conductors. Care should be exercised in keeping these values below a certain critical value, which depends on the

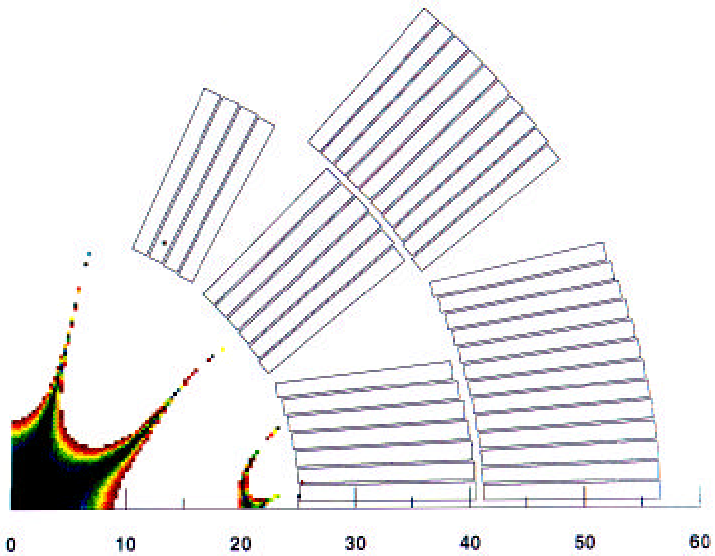


Figure 1: Cross-section of the HFM mechanical model obtained from ROXIE.

Block Number	No. of Conductors	Positioning Angle (degrees)	Inclination Angle (degrees)	Inner Radius (mm)
1	13	0.78	0.0	41.06
2	10	29.90	39.0	41.06
3	7	1.28	0.0	25.0
4	6	27.50	39.5	25.0
5	4	51.25	62.0	25.0

Table 1: Geometrical data for the model magnet cross-section.

Insulated Cable Height (mm)	15.62
Insulated Cable Inner Width (mm)	1.5231
Insulated Cable Outer Width (mm)	1.7899
Bare Cable Height (mm)	15.40
Bare Cable Inner Width (mm)	1.325
Bare Cable Outer Width (mm)	1.588
Number of strands	38
Diameter of strands (mm)	0.8080
Cu/Superconductor Ratio	1.3
Cabling Angle (degree)	16

Table 2: Cable (NbTi) dimensions and properties for the model magnet.

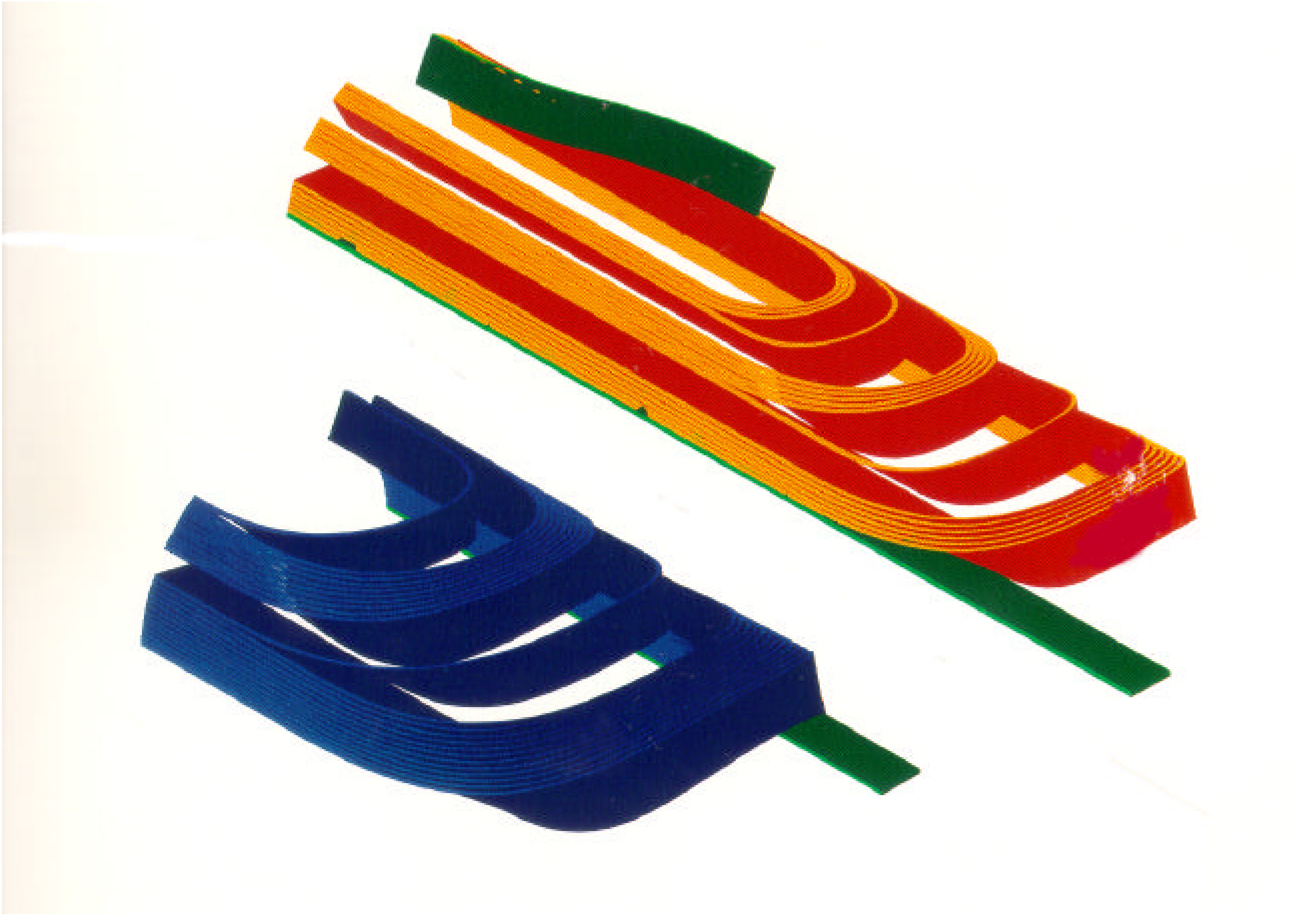
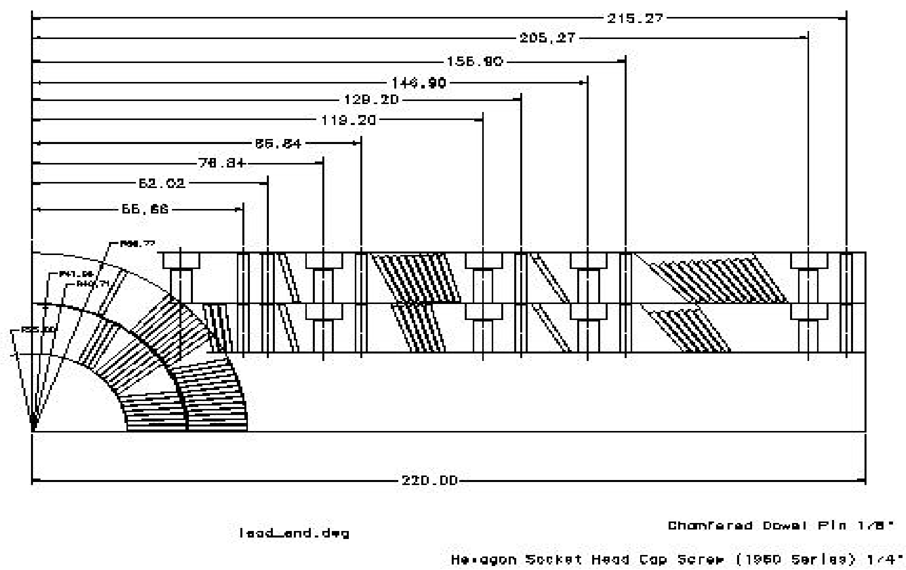


Figure 2: Lead ends of the inner and outer coils of the model magnet.

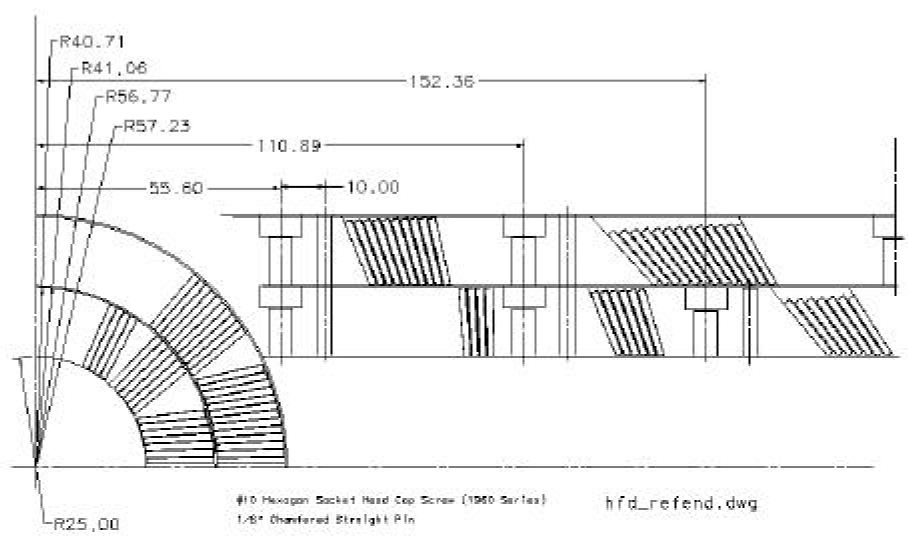
type of conductor used, mechanical properties of the cable and prior user's experience in coil winding with the same cable. It is claimed that a de-keystoning factor can also be defined in ROXIE to account for the change in shape of the cable at the ends, caused by the winding process. However, the only way we found in ROXIE to account for cable de-keystoning was by the introduction of inter-turn spacers in between the conductors.

2.3 End parts positioning

To avoid using spliced joints, it was decided to wind both the inner and outer layers from the same cable. This required winding of the outer layer coil on top of a pre-wound inner layer coil on the mandrel. Thus, it was necessary to fix the outer layer parts to the mandrel through the holes on the inner layer end parts. Therefore, holes needed to mount the parts on the mandrel were aligned together for the inner layer and outer layer end parts to lie on top of one other as shown in Fig. 3.



(a) Lead end



(b) Return end

Figure 3: YZ cross-section for the lead end and return end.

3. End Parts Manufacturing

The shape and position of the coil blocks obtained from ROXIE's optimization techniques determine the shape of the end-parts. ROXIE outputs the surfaces to be machined in terms of 9 polygons, which describe the end-part surfaces. Three different ways of sectioning these polygons are provided in ROXIE:

- Equiangular slicing of the ellipses in the sz planes (Etype 10).
- Equidistant slicing of the ellipses (Etype 11).
- Equitangential slicing of the upper and lower ellipses (Etype 12).

Both the equiangular and equidistant slicing of the ellipses requires the use of a spherical cutter to cut end part surfaces, which are defined by the 9 polygon surfaces. This makes the machining process to be very time-consuming and expensive. On the other hand, an equitangential slicing of the ellipses offers the opportunity of using a cylindrical cutter, whereby only the upper and lower polygon surfaces could be used for the machining of the end-parts. This makes machining to be less time consuming and relatively less expensive. Therefore, equitangential slicing (Etype 12) of the ellipses was performed to define the rulings for end parts manufacturing. A set of 72 rulings was used to define the tool path for machining of the end parts.

The end parts were made out of 6061 T-651 aluminum tubes, which were machined to the appropriate inside and outside diameters corresponding to the inner and outer coil cross-section. The end parts were then cut out of these machined tubes by a wire EDM process. It should be mentioned that the residual stresses in the machined tubes could cause changes in the dimensions of the end parts, after electric discharge machining process. To prevent any dimension changes due to the residual stresses, the machined tubes were given a stress-relieve annealing treatment. This was achieved by heating the tubes in a furnace at 343 °C for 1 hour followed by an overnight cool in the furnace.

Fig. 4 shows a schematic of the end parts manufacturing process. ROXIE provided output data in an ASCII format giving the X, Y and Z coordinates for the 72 points on the rulings for 9 different polygon surfaces. A program was written by V. Kashikin to extract the 72 ruling points on the upper and lower polygons only, and to read them in AutoCAD in a DXF format. Thus, a set of 72 rulings for surfaces defining the end parts could be obtained. These data were transmitted electronically to Lawrence Berkeley National Lab (LBNL) for the machining of the end parts via a 6-axis wire EDM (electric discharge machining). EDM of the end parts was chosen for parts manufacturing rather than conventional 5-axis machining techniques due to the substantial savings in cost offered by the EDM technique. For a comparison, it was found that the electric discharge machining of the end parts was approximately three times cheaper than conventional machining. An alternative methodology for end parts manufacturing can use IDEAS instead of AutoCAD as the intermediate step.

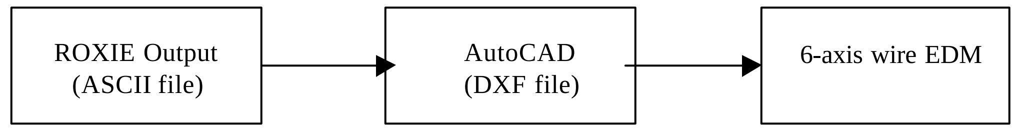


Figure 4: Schematic of the methodology followed for end parts manufacturing.

Note that if it is not required to make and archive drawings for the end parts, and if the end parts are not put through a very thorough inspection process, then the above methodology presented in Fig. 4 for end parts manufacturing is self-sufficient by itself. This would require conveying information (such as location of the holes) to the machinist in terms of hand-made sketches. Otherwise, Fig. 5 shows a schematic of the methodology followed for generating end parts drawings from the ROXIE output. Note that the same process is required if BEND is used instead of ROXIE for designing the end parts. Due to the complex 3-dimensional shape of the end parts (as seen in Fig. 6 and Fig. 7), it is necessary to make a 3-D solid model of the end parts before generating the 2-D drawings. This is a very time consuming process and takes significant efforts and resources of the personnel involved in the project. Note that to shorten the process shown in Fig. 5, one of the intermediate steps of going through ANVIL can be bypassed. It should be mentioned here that the '*gen*' files made in ANVIL are used at Fermilab for both the machining and inspection of the end parts. However, it is still possible to bypass this extra intermediate step of going through ANVIL. This would be helpful because there are more personnel at Fermilab who are trained to use IDEAS software than those who are trained to use ANVIL. Achieving of this goal would require a combined effort on part of the part designer, machinist and the inspection crew. Note that even after elimination of this intermediate step, producing of drawings for archival purposes is still a very time consuming process.

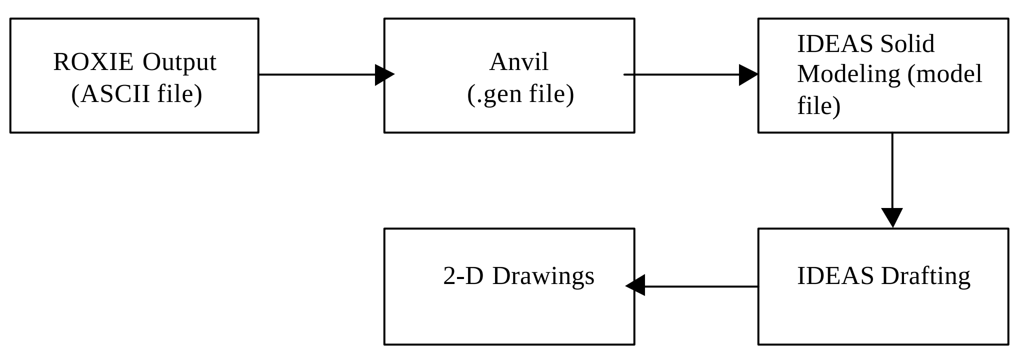


Figure 5: Schematic of the methodology used to produce end parts drawings.

Figure 6: 3-D solid model for the outer layer end parts for the first mechanical model magnet.

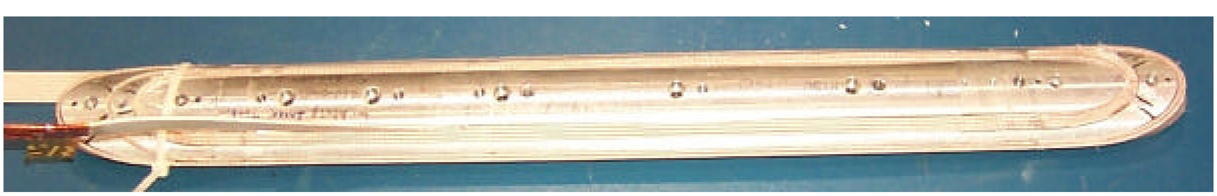


Figure 7: Photograph of a partially wound inner coil.

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Appendix

The drawings for the end parts for the first mechanical model magnet can be found in the XDCS system. There are 18 drawings with part numbers ranging from 376031 to 376048. The drawings for all other parts such as transition, pole pieces and wedges are archived and can be obtained from L. Aslip as sketch numbers ranging from SY012599-1 to SY012599-8.

References

[1] T. Arkan et al., "Conceptual design of the Fermilab Nb_3Sn high field dipole model," PAC-99, New York, 1999.

[2] ROXIE, Routine for the optimization of magnet X-sections, inverse field computation and coil end design, Proceedings of the First International Roxie Workshop, Geneva, March 1998.